Lower current-driven exchange switching threshold in noncollinear magnetic junctions under high spin injection

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Abstract

Current-induced switching is considered in a magnetic junction. The junction includes pinned and free ferromagnetic layers which work in the regime of the high spin injection. It is shown that in such a regime the exchange magnetization reversal threshold can be lowered up to two times when the axes of the layers are noncollinear.

1 Introduction

The effect of current-driven switching in magnetic junctions [1] attracts continuing attention because of possible using this phenomenon for high-density information processing. One of the most important problems is lowering the current density threshold corresponding to instability of the initial magnetic configuration and switching it to another one with different resistance. Various ways have been proposed to solve the problem, namely, using magnetic semiconductors with their lower saturation magnetizations [2], choosing the layer materials with proper spin resistances [3], and so on. In this note, we consider an additional possibility of lowering the threshold current density corresponding to instability and switching the magnetic configuration of the magnetic junction.

2 The model

We consider a magnetic junction consisting of a pinned ferromagnetic layer 1, free ferromagnetic layer 2, an ultrathin spacer in between, and nonmagnetic layer 3 closing the electric circuit. The current flows perpendicular to the layer

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planes (CPP mode). The free layer thickness L is assumed to be small in comparison with the spin diffusion length in that layer and the domain wall thickness. In such conditions, the macrospin approximation [4] is applicable. In this approximation, the modified Landau–Lifshitz–Gilbert (LLG) equation contains additional terms describing two different mechanisms of the spin-polarized current influence on the magnetic lattice, namely, the spin torque transfer effect [5, 6] and the spin injection effect [7]. The relative role of these mechanisms depends on the system parameters, specifically, the Gilbert damping constant. It has been shown [4] that with suitable choice of the layer spin resistances and not too small damping constant, the injection mechanism predominates over the spin torque transfer mechanism. Such a situation is assumed below.

We use a coordinate system with x axis along the current direction and yz plane parallel to the layers plane. The easy axis of free layer 2 is parallel to z axis, while the easy axis of layer 1 is oriented at some angle with respect to z axis.

3 Switching conditions under high spin injection

When the spin injection predominates over the spin torque transfer, the LLG equation has the first integral in form of a magnetic energy consisting of the Zeeman energy, the anisotropy energy, the demagnetization energy, and the nonequilibrium *sd* exchange energy proportional to the spin-polarized current density [8, 9]. The magnetic energy is a function of the angles determining orientation of the free layer magnetization with respect to the easy axis of the layer, the external magnetic field, and the pinned layer magnetization (which is parallel to the easy axis of this layer). The angles depend on the current density because of the sd exchange interaction. The minima of the magnetic energy correspond to the stable equilibrium states. The switching occurs when the stable equilibrium state of the system disappears or converts to unstable one (which corresponds to a maximum of the energy).

We assume below that the spin resistance [10] of the free layer is much lower than the spin resistances of the pinned and nonmagnetic layers.

Under assumptions mentioned, the (dimensionless) magnetic energy with the current direction corresponding to the electron flow from the pinned layer to the free one takes the form [9]

$$U == \frac{H}{H_a}\cos(\theta-\beta) - \frac{1}{2}\cos^2\theta - \frac{j}{j_0}\cos(\theta-\theta_1), \tag{1}$$

$$j_0 = \frac{eH_aL}{\mu_{\mathrm{B}}\alpha\tau Q_1}. \tag{2}$$

Here the following notations are used: H is the external magnetic field, H_a is the anisotropy field of the free layer, θ and β angles determine directions of the free layer magnetization and the external magnetic field, respectively, reckoned from the free layer easy axis (z axis), θ_1 is analogous angle for the pinned layer, α is

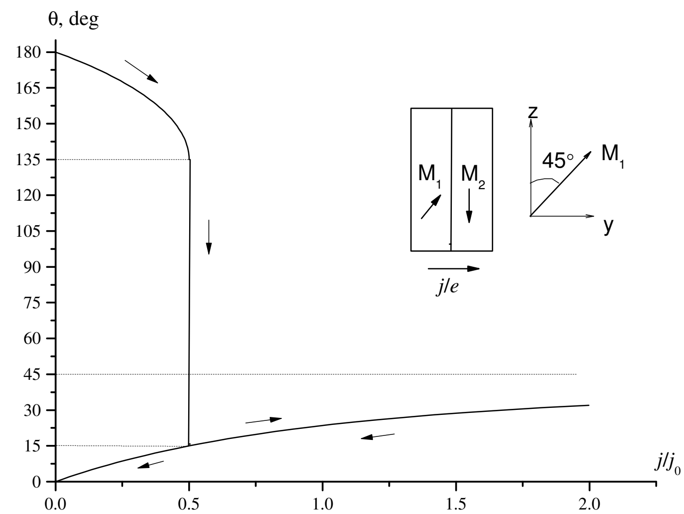

Figure 1: Switching magnetic junction with noncollinear initial configuration. The free layer magnetization orientation is shown versus the current density through the junction. The arrows indicate direction of the current change. Vectors $\mathbf{M}_1$ and $\mathbf{M}_2$ denote magnetizations of the pinned and free layers, respectively.

the dimensionless constant of *sd* exchange interaction, τ is the spin relaxation time, Q_1 is the spin polarization of the pinned layer conductivity, μ_{B} is the Bohr magneton,

In absence of the magnetic field ($H = 0$) and the current ($j = 0$), there are two stable configurations, $\theta = 0$ and $\theta = 180°$. At $H = 0$ and $\theta_1 = 0$, the antiparallel relative orientation of the ferromagnetic layers ($\theta = 180°$) becomes unstable, and switching occurs to parallel configuration ($\theta = 0$) at $j = j_0$.

4 Switching noncollinear configurations

The stability analysis shows that the instability occurs at lower threshold current density if the initial configuration is not collinear. The minimal threshold current density $j_{\mathrm{th}} = j_0/2$ takes place when the angle between the easy axes of the pinned and free layers is equal to 135°.

The numerical results are shown in fig. 1. Let the pinned layer easy axis and the magnetization vector $\mathbf{M}_1$ be directed at the angle of $\theta_1 = 45°$ with respect to z axis, while the initial (in absence of the current) direction of the free layer magnetization corresponds to $\theta = 180°$. When the current through

magnetic junction is turned on and increases, the magnetization vector $\mathbf{M}_2$ of layer 2 deviates from the initial direction. When the current density reaches value $j = j_0/2$, that vector takes the position $\theta = 135°$. At that moment, instability occurs and vector $\mathbf{M}_2$ abruptly turns to a new position $\theta = 15°$. At further increase in current, vector $\mathbf{M}_2$ tends to stand parallel to $\mathbf{M}_1$. If the current is turns off, vector $\mathbf{M}_2$ takes the position $\theta = 0$. Thus, the switching of vector $\mathbf{M}_2$ is realized from $\theta = 180°$ to $\theta = 0$ position with threshold current density $j_{\rm th} = j_0/2$, half as much as the threshold for collinear configuration.

If magnetic field H is applied along $\mathbf{M}_1$ vector, the threshold current density reveals further decrease to

$$j_{\rm th} = \frac{j_0}{2}\left(1 - \frac{2H}{H_a}\right). \tag{3}$$

At H value close to but slightly less than the halved anisotropy field $H_a/2$, the instability threshold can be lowered considerably. Note, that participation of the magnetic field does not prevent locality of the effect, because the magnetic field $H < H_a/2$ cannot do switching alone, without the current.

The switching effect leads to change in resistance; this is of the same origin as the well-known giant and tunnel magnetoresistance effects. The current density through a tunnel junction with $\chi = \theta - \theta_1$ angle between the layer magnetizations is [11]

$$j = j_p \cos^2 \frac{\chi}{2} + j_a \sin^2 \frac{\chi}{2}, \tag{4}$$

where j_p and j_a are the current densities for parallel ($\chi = 0$) and antiparallel ($\chi = 180°$) configurations, respectively. In the example considered ($\theta_1 = 45°$), χ angle is equal to $\chi_1 = 135° - 45° = 90°$ just before the switching and $\chi_1 = 15° - 45° = -30°$ just after the switching. Therefore, the junction resistance relative change due to the switching is

$$\frac{R_1 - R_2}{R_2} = \frac{\sqrt{3}}{2}\frac{\rho}{2+\rho}, \tag{5}$$

where $\rho \equiv (j_p - j_a)/j_a$ is the standard magnetoresistance ratio [12] corresponding to the switching from one collinear configuration to another (opposite) one.

The threshold of the switching by a magnetic field can be lower up to two times also when the field is applied at an angle to the easy axis of the layer, in comparison with the collinear configuration [13]. In our case, the field is of exchange nature, but the result is similar. It should have in mind, however, that the exchange switching, unlike the conventional switching by a magnetic field, is localized at the atomic level. This fact opens new practical possibilities.

5 Conclusion

The calculations show that the threshold current density corresponding to switching the free layer magnetization to opposite direction can be lowered up to two

times if the pinned layer of the junction is noncollinear with the easy axis of the free layer. Such an effect allows varying conditions of experiments.

With more complex anisotropy when several easy axes present a many-level switching is possible in a magnetic field [14]. The generalization of this result to the exchange switching by a spin-polarized current is of great interest.

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References

[1] J. A. Katine, F. J. Albert, R. A. Buhrman, E. B. Myers, and D. C. Ralph, Phys. Rev. Lett. **84**, 3149 (2000).

[2] M. Watanabe, J. Okabayashi, H. Toyao, T. Yamaguchi, and J. Yoshino, Appl. Phys. Lett. **92**, 082506 (2008).

[3] Yu. V. Gulyaev, P. E. Zilberman, A. I. Krikunov, and E. M. Epshtein, Techn. Phys. **52**, 1169 (2007).

[4] Yu. V. Gulyaev, P. E. Zilberman, A. I. Panas, and E. M. Epshtein, J. Exp. Theor. Phys. **107**, 1027 (2008).

[5] J. C. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996).

[6] L. Berger, Phys. Rev. B **54**, 9353 (1996).

[7] Yu. V. Gulyaev, P. E. Zilberman, E. M. Epshtein, and R. J. Elliott, JETP Lett. **76**, 155 (2002).

[8] R. J. Elliott, E. M. Epshtein, Yu. V. Gulyaev, and P. E. Zilberman, J. Magn. Magn. Mater. **271**, 88 (2004).

[9] E. M. Epshtein, J. Commun. Technol. Electron. **54**, 323 (2009).

[10] E. M. Epshtein, Yu. V. Gulyaev, and P. E. Zilberman, J. Magn. Magn. Mater. **312**, 200 (2007).

[11] Y. Utsumi, Y. Shimizu, and H. Miyazaki, J. Phys. Soc. Japan **68**, 3444 (1999).

[12] M. Guilliere, Phys. Lett. A **54**, 225 (1975).

[13] S. Chikazumi, Physics of Magnetism (Clarendon, Oxford, 1997).

[14] T. Uemura, T. Marukame, K. Matsuda, and M. Yamamoto, IEEE Trans. Magn. **43**, 2791 (2007).